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A "Moore's Law"-like approach to roadmapping photovoltaic technologies

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ABSTRACT

The photovoltaics industry has made steady progress over the past 40 years toward increasing solar cell and module efficiencies while incrementally lowering the initial installed cost of photovoltaic systems. These two factors dominate in lowering the cost of solar electric energy (in ¢/(kW-h)) as it approaches parity in cost with electric energy produced conventionally using coal, nuclear, or natural gas. An interesting question regards whether there is a relationship that describes the evolution of photovoltaics Levelized Cost of Energy (LCOE) similar to Moore's Law characterization of microelectronics evolution of transistor size and density. With some caveats, we believe a similar PV relationship can be defined; the purpose of this paper is to propose and discuss a basis for this relationship. To achieve parity the installed cost of PV systems needs to be reduced by 50% from approximately $\$600/m^2$ to $\$300/m^2$ with a concurrent increase in c-Si module efficiency to 24% AM1.5. The trajectories in time needed to drive a technology roadmap for lowering the installed cost and for increasing the module efficiency to achieve parity are discussed. Also, a new methodology for calculating LCOE for PV systems is proposed and discussed in Appendix.

Contents

1. Introduction

The photovoltaics industry has made steady progress over the past 40 years toward increasing solar cell and module efficiencies while incrementally lowering the initial installed cost of photovoltaic systems. These two factors dominate in lowering the cost of solar electric energy (in ¢/(kW-h)) as it approaches parity in cost with conventionally produced energy.

The objective of the work reported in this paper is to develop and exercise a simple analytical model as a first-principals tool to examine the tradeoffs between module efficiency and the total lifetime cost of a PV system in achieving parity in the cost of PV- and conventional-generated energy in a specified year.

One metric used to benchmark progress of photovoltaic systems is the cost per peak Watt electric or $\$/W_{pe}$ (defined here as C_W). ($W_{pe}=\eta\phi_s$, where η is the module power conversion

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efficiency and ϕ_s is the maximum solar flux at AM1.5; i.e. $\phi_s = 1$ kW (solar)/m^2). This metric (C_w) is quite useful in tracking development of PV cell, module, and systems technologies and comparing the cost per peak Watt of different competing technologies, and is therefore quite helpful in addressing the requirements of the PV user. Another parameter, more suited to the PV manufacturing and scientific communities, is the cost of PV cells and modules in \$/m^2 (defined here as C_m). These metrics are related in the following manner: $C_m = C_w(\eta\phi_s)$ or $C_w = C_m/(\eta\phi_s)$. This shows that C_w is a function of two very important variables: C_m and η. This analysis is focused on the use of C_m and η separately to examine the relative impact of each variable on Levelized Cost of Energy (LCOE), and thereby sets the stage for determining their separate development trajectories necessary to achieve cost parity with conventional energy within a prescribed year.

In microelectronics Moore's Law has been a very useful relationship to gauge dimensional scaling of transistor size and density on state-of-the-art Si CMOS chips using a very simple, easy to visualize, yet powerful concept. Moore's Law states "The number of transistors per cm^2 fabricated on a microelectronics chip doubles every two–three years" [1].

The question related to photovoltaics addresses whether there is a relationship that describes the evolution of photovoltaics LCOE similar to Moore's Law characterization of microelectronics evolution of transistor size and density. With some caveats, we believe a similar PV relationship can be defined; the purpose of this paper is to propose and discuss an analytical basis for this assertion. An important disclaimer is the analysis discussed in this paper is intended to illustrate simple principles that help visualize the dominant factors impacting LCOE in PV cell and module development and not to perform highly accurate and comprehensive analyses. The NREL "Solar Advisor Model" is a good tool for performing such analyses [2].

Another question is how the analytical model and the results obtained and discussed herein relate to other PV roadmaps currently in the literature, e.g., [3–11,12]. The analytical model reported in this paper illustrates the need to roadmap simultaneous technological development of solar cells and modules to obtain increased efficiency at lower cost and to concurrently roadmap lowering the initial installed cost of PV systems. Both developments are required to lower the cost of solar electric energy to reach parity with conventionally-generated energy within a given year. A simple model reported herein enables quick analysis of the relative contributions that solar cell/module efficiency and initial PV system installation costs make in lowering the cost of solar electric energy. This perspective can be useful in allocating limited R&D resources. Other studies tend to focus on important PV systems technical factors such as system efficiency or economic/public policy factors such as tax incentives to subsidize systems installation and operating costs. One example of an excellent study of the cost competitiveness of solar PV power leading to penetration of solar energy into the utility-scale market is found in [12]. Similarly, [3] reports a broad survey of current, comprehensive roadmaps "to provide a comparative technology assessment and roadmapping process to examine key characteristics for leading electricity generation technologies and predict trends in cost reduction and growth potential". This is a good example of the scope of several published PV technology roadmaps that briefly discuss development of silicon solar cell and module technologies to increase their efficiency and lower their cost, in the broader context of assessing their application in utility-scaled generation systems [5–11,12]. Conversely, the *Technology Roadmap—Solar photovoltaic energy* published in 2010 by the International Energy Agency [5] is a very comprehensive analysis of PV solar cell technologies and related topics, such as regulatory framework and support incentives, technology development, R&D support, and international collaboration. The purpose of their roadmap is to provide "… a basis for greater international collaboration and identifies a set of effective technology, economic, and policy goals and milestones that will allow PV to deliver on its promise and contribute significantly to world power supply". The technological focus of their roadmap is centered on solar cell and module technologies, with little discussion of other PV balance of systems issues. The content of this roadmap is representative of several PV roadmaps that address important, higher level market-driven issues related to the growing commercialization of PV technologies in a variety of regional markets. A broad discussion of renewable energy roadmaps can be found in [4].

Appendix compares a new analytical formulation for LCOE used in this paper with the conventional formulation used by other authors.

2. Analytical model for LCOE of a PV system

The purpose of the following analysis is to calculate the Levelized Cost of Energy (LCOE) over the life of a PV system located in Phoenix, AZ, and to determine the relationship of LCOE to the installed cost per m^2, C_m, and the module power conversion efficiency, η. We begin with calculation of the Levelized Cost of Energy in ¢/kW-h

$$LCOE = (Total\ lifetime\ cost\ of\ a\ PV\ system)\ /(Total\ Electrical\ Energy\ produced\ by\ the\ system)$$

$$Ct = Total\ Lifetime\ cost\ of\ the\ PV\ system$$

$$Ct = \sum_{n=1}^{n=N}\left[\frac{C_{mn}}{(1+D)^n} + \frac{C_{mn}\times I\times N}{(1+D)^n} + \frac{C_{omn}}{(1+D)^n} + \frac{C_{inv}}{(1+D)^n}\right], \tag{1}$$

where

C_{mn} = *initial installed system* cost and *Cm divided by system life in N years, in units of* $\frac{\$}{m^2-yr}$,

C_{omn} = *the annual operations and management cost in units of* $\frac{\$}{m^2-yr}$,

D = *the discount rate*,

I = *interest rate on* 30 *and* 35 *year corporate bonds*,

N = *the lifetime of the system in years*,

M = *the year in which the inverter is replaced*,

C_{inv} = *the installed cost of an inverter depreciated linearly over* $N-M$ *years*,

($C_{inv} = 0$ *for* $n = 1$ *to* $n = m-1$) *and*

Wte = *total electrical energy produced by the PV system over its life in* (kWe − h)/m^2

$$Wte = \sum_{n=1}^{n=N} Q_n(1-i)^n \tag{2}$$

where[1]

Q_n = *the electrical energy delivered by the PV system in its nth year of operation, and*

i = *the annual degradation rate of the system*

$$LCOE = \frac{Ct}{Wte} = \frac{\sum_{n=1}^{n=N}[(C_{mn}/(1+D)^n) + ((C_{mn}\times I\times N)/(1+D)^n) + (C_{omn}/(1+D)^n) + (C_{inv}/(1+D)^n)]}{\sum_{n=1}^{n=N} Q_n(1-i)^n} \tag{3}$$

[1] Some authors express *Wte* as $Wte = \sum_{n=1}^{n=N} Q_n(1-i)^n/(1-D)^n$ which applies the discount rate, *D*, to the solar energy incident on the PV system in the *n*th year. As discussed in Appendix, this author thinks this is an incorrect application of the discount rate.

$$LCOE = \frac{Ct}{Wte} = \frac{\sum_{n=1}^{n=N}[(C_{mn}/(1+D)^n)+((C_{mn}\times I\times N)/(1+D)^n)+(C_{omn}/(1+D)^n)+(C_{inv}/(1+D)^n)]}{Q_{avg}\sum_{n=1}^{n=N}(1-i)^n} \tag{4}$$

where

Q_{avg} = *average electrical energy produced in Phoenix by the system in the first year.*

$Q_{avg} = 5.38 \times 365 \times C_f \times \eta_c,$

where

C_f = *Capacity Factor – reduction in cell efficiency by module and other obscuration effects*

and

η_c = *Cell Power Conversion Efficiency.*

In Phoenix the average daily insolation is 5.38 kW-h/m^2-day averaged over 365 days [13].

A common assumption consistent with the first order nature of this analysis is the annual operation and management cost, C_{omn}, and the annual depreciation cost, C_{inv}, of the new inverter installed in the mth year are directly proportional to the annual depreciation cost of the initial installation, C_{mn}. The constant of proportionality for C_{mn} is typically P_{om}=0.0012 [14] and for C_{inv} is P_{inv}=0.0763 [15,16]. Also, as defined above, C_{mn} is assumed to be a constant equal to C_m/N. These are key approximations in that they reduce the relationship for LCOE to a simple linear equation, as shown below.

$$LCOE = \frac{Ct}{Wte} = \frac{\sum_{n=1}^{n=N}[1/(1+D)^n+(I\times N)/(1+D)^n+P_{om}/(1+D)^n+P_{inv}/(1+D)^n]}{5.38\times 365\times\sum_{n=1}^{n=N}(1-i)^n}\times\left(\frac{C_{mn}}{C_f\times\eta_c}\right) \tag{5}$$

$$LCOE = Constant_m \times \left(\frac{C_{mn}}{C_f\times\eta_c}\right), \tag{6}$$

where

$$Constant_m = \frac{\sum_{n=1}^{n=N}[1/(1+D)^n+(I\times N)/(1+D)^n+P_{om}/(1+D)^n+P_{inv}/(1+D)^n]}{5.38\times 365\times\sum_{n=1}^{n=N}(1-i)^n} \tag{7}$$

Again, in the spirit of this analysis, the residual value of the system at its end-of-life is assumed to be zero and taxes are not included. However, the issuance of corporate bonds at an annual interest rate of I and maturing in the Nth year are included to raise the capital for the initial installation of the system. This approximate relationship illustrates that LCOE is linearly dependent on the PV system initial annualized cost of installation, C_{mn}, and is inversely proportional to the cell efficiency, η_c. The module efficiency, η, is equal to the cell efficiency, η_c, reduced by the module factor, C_f, or $\eta = C_f \times \eta_c$. Since $C_m = C_w(\eta\phi_s)$, LCOE also is given by

$$LCOE = Constant_m \times \varnothing_s \times \left(\frac{C_{mn}}{\eta\times\varnothing_s}\right) = Constant_w \times (C_{wn}), \tag{8}$$

where

$$Constant_m \times \varnothing_s = Constant_w \tag{9}$$

and

$$C_{wn} = \frac{C_{mn}}{\eta\times\varnothing_s}. \tag{10}$$

C_{wn} *is in units of* $\frac{\$}{\text{W peak Electric} - \text{yr}}$,

C_{mn} *is in units of* $\frac{\$}{\text{m}^2 - \text{yr}}$ and $\varnothing_s = 1000\frac{\text{W (solar)}}{\text{m}^2}$.

This shows that the LCOE is also linearly proportional to C_{wn} and C_w However, because C_{wn} and C_w combine two equally important variables, C_{mn} and η, in one variable, the relationship

$$LCOE = Constant_m \times \left(\frac{C_{mn}}{C_f\times\eta_c}\right) \tag{6}$$

is better suited for independently roadmapping C_m and η_c than the relationship

$$LCOE = Constant_w \times C_{wn} \tag{8}$$

As an example, for the LCOE of a PV system to reach parity with the cost of energy produced by conventional means of generation, the decreasing trajectory for the PV system's LCOE combined with a given path for improving the efficiency of c-Si cells, a technology roadmap can be specified for lowering the initial installed cost of the system. With this simple analytical model, LCOE, η_c and C_m, can be easily studied and visualized to lower the LCOE with time to reach parity with conventional generation systems.

While an analysis was not performed explicitly to evaluate the sensitivity of LCOE to the initial installed system cost or system efficiency, the linearized model expressed by Eq. (8) indicates LCOE is directly proportional to the initial system installed cost and inversely proportional to system efficiency. Furthermore the response of the model to the fractional variation of the initial system installed cost, $|\Delta(C_m)/C_m|$, and the fractional variation of the system efficiency $|\Delta(\eta)/\eta|$, is further constrained by a historical learning curve for PV modules manufactured over a period of 30+ years (Fig. 2). This is discussed further in Section 3 below.

3. Benchmarking, validation, and sensitivity of the analytical model for LCOE

3.1. Model benchmark process

Before proceeding, the accuracy of this analytical model is investigated by comparing results obtained applying this model to a 10-MW flat-plate Reference System with results obtained using the National Renewable Energy Laboratory's computer model, "Solar Advisor Model" [2], applied by the Department of Energy to the same Reference System [17]. Both models are first benchmarked using 2005 initial installation cost, operational cost and performance data obtained by DOE for 30 operating systems across the U.S. The LCOEs obtained for the two models are then compared using results for cost for their application to the Reference Systems installed in 2011 and in 2020.

3.2. 10-MW flat-plate DOE Reference System

The 10-MW Flat-plate DOE Reference System is specified in Table 1. Located in Phoenix, AZ, the version of this system installed in 2005 has been rigorously benchmarked against cost and performance information obtained from electric utility sources for approximately 30 installations and from web-based sources for more than 300 systems located across the United States. Projections for 2011 and 2020 are based on inputs from a variety of sources including technical staff in the PV industry [16].

The analytical model reported in this paper uses system-based parameters given for the Reference System. For example the system efficiency used for 2005 is 13.5% (module efficiency) × 92% (DC–AC conversion efficiency) for a combined system efficiency of 12.4%. The results of this analysis are given in Fig. 1.

Table 1
2005 Benchmarked parameters, 2011 and 2020 projections for modeling of 10-MW flat-plate Utility Reference System [16].

System element	Units	2005	2011	2020
System location	Phoenix			
System size	MW	10	11.85	14.82
Module price	$/Wdc	3.30	2.20	1.25
Conversion efficiency	%	13.5	16	20
Module size	Wpdc	150	178	222
Inverter price	$/Wac	0.46	0.35	0.25
Inverter size	kW	150	178	222
DC–AC Conversion efficiency	%	92	96	97
Inverter life/replacement	Years	10	15	20
Other BOS costs	$/Wdc	0.97	0.73	0.61
Installation	$/Wdc	0.27	0.16	0.10
Other direct/indirect	$/Wdc	0.55	0.46	0.37
Installed system price	$/Wdc	5.55	3.90	2.58
Lifetime	Years	30	35	30
Degradation	%/Yr	1	1	1
System derate	%	5	5	5
O and M cost (not including inverter replacement)	% Installed price	0.15	0.10	0.10
Levelized Cost of Energy (LCOE)	$/kWac	0.15–0.22	0.10–0.15	0.06–0.09

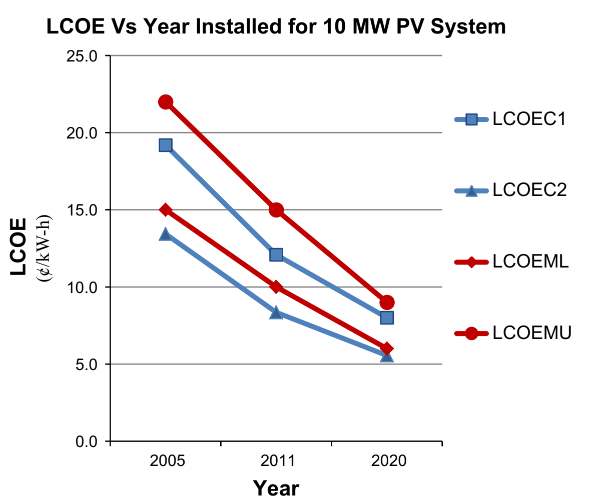

Fig. 1. Numerical results for LCOE obtained using the analytical model applied to the 10-MW Flat-plate Reference System for: LCOEC1: D=0.05, i=0.01, and I=7%; LCOEC2: $D=i=I=0$ (discount rate, degradation rate, and bond interest=0); LCOEML: lower results for LCOE obtained by DOE using the NREL SAM; and LCOEM: higher results for LCOE obtained by DOE using the NREL System Advisor Model applied to the Reference System [7].

The DOE Reference System illustrates the initial installation costs dominate most of the other costs related to annual operation and maintenance and replacement of the inverter. The annual operation and maintenance costs for the 2005 system are only 0.15% of the installation cost and the inverter cost is less than 8% of the installed cost amortized over 10 years of the system life.

One cost element that can substantially impact the LCOE of a PV system is the cost of capital related to issuing corporate bonds for the life of the system to pay the initial installation costs. In this work we assume the life of the bond to equal the life of the system and the annual interest rate to be 7%. This rate is a bit high (5% or less would be more current), but was chosen to compensate for many other costs not included in this analysis.

The variance of LCOEC1 from LCOEMU for 2005 is 17%; for 2011 the variance is 20%; and for 2020 the variance is approximately 11%. These margins of variance are consistent with the intent to use this analytical model to explore a possible basis of a technology roadmap for cell and module efficiency and their cost in $/m^2. This is driven by a required trajectory lowering LCOE in time to achieve cost parity with conventional energy sources within a given year. This linear analytical model therefore can be used to state a "Moore's Law"—like relationship for PV cell technology, which is addressed in Sections 4 and 5 below. First, however, the sensitivity of this model to variation of three representative input parameters is examined in the next section.

3.3. Sensitivity analysis

As mentioned above, a limited analysis was performed to evaluate the sensitivity of LCOE to variation of three input variables: the capacity factor, C_f, the discount rate, D, and the system degradation rate, i. Two of these variables, the capacity factor and the discount rate, were chosen because they were expected to be the most influential in their impact on LCOE, as found by [12]. The system degradation rate was chosen because it was expected to have little impact on LCOE. Each of these parameters is varied $\pm 40\%$ while holding all other parameters constant. The results of this analysis are given in Fig. 2 where one sees the change in value of LCOE with increasing capacity factor and increasing discount rate is negative for both cases. Conversely, increasing degradation rate results in a positive change of LCOA. The inverse relationship between LCOE and discount rate is shown in Eq. (3), where LCOE is proportional to $1/(1+D)^n$. As the present value of future costs of a PV system decreases with increased discount rate, the levelized cost, LCOE, is decreased.

The capacity factor is seen to have the largest impact. A 40% increase in the capacity factor results in a 30% decrease in LCOE, and a 40% decrease in the capacity factor yields nearly a 70% increase in LCOE. This points to the need to maximize the amount of sunlight available per day to be coupled into the solar cells in a PV generation system.

The discount rate is the next most sensitive input parameter, with a 40% increase in discount rate resulting in a 20% decrease in LCOE, and a 40% decrease in discount rate yielding a 20% increase in LCOE.

The Systems Degradation Rate is seen to have the least impact on changing LCOE. As the System Degradation Rate varies $\pm 40\%$, the LCOE increases/decreases $\pm 5\%$ indicating the cost of solar PV electric energy is rather robust to system variations.

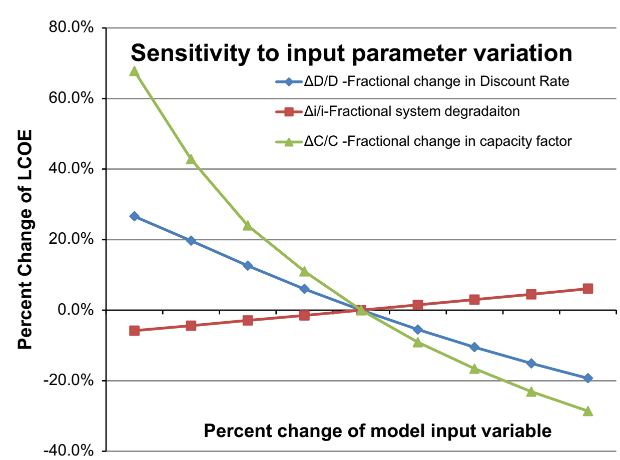

Fig. 2. Sensitivity analysis for variation of input parameters discount rate, system degradation, and capacity factor.

4. Moore's Law equivalent for PV technologies

According to Moore's Law the number of transistors per cm^2 fabricated on a microelectronics chip (typically microprocessor and memory) doubles every 2–3 years. This rate of advance of integrated circuit technology in the 2011 International Technology Roadmap for Semiconductors (ITRS) was driven by a required annual reduction of the transistor's "intrinsic delay time" (τ_d) of 13%/year. As a result, the linear dimensional scale of the transistors is reduced over the same period by $\sqrt{2}$. Moore's Law has proven valid through several changes in microelectronics technology beginning with bipolar transistors, migrating to p-channel, n-channel, and finally with complementary MOSFETs or CMOS.

This stimulates an interesting question for photovoltaics: Is there a relationship that describes the evolution of photovoltaics LCOE similar to Moore's Law? If so, what is the independent variable for PV comparable to τ_d for ICs? To address this question, we first select C_{wn} ($/Watt) as the independent variable for PV and start with[2]:

$$LCOE = Constant_m \times \left(\frac{C_{mn}}{C_f \times \eta_c}\right) \tag{6}$$

and

$$C_{wn} = \frac{C_{mn}}{\eta \times \varnothing_s} \tag{10}$$

Vary LCOE as $\Delta(LCOE)$—[note that $\eta = C_f \times \eta_c$]:

$$\Delta(LCOE) = (Constant_m \times (\eta \times \Delta(C_{mn}) - C_{mn} \times \Delta\eta))/\eta^2 \tag{11}$$

$$\Delta(LCOE)/\left(Constant_m \times \frac{C_{mn}}{\eta}\right) = \Delta(C_{mn})/C_{mn} - \Delta(\eta)/\eta \tag{12}$$

$$\frac{\Delta(LCOE)}{LCOE} = \frac{\Delta(C_{mn})}{C_{mn}} - \frac{\Delta(\eta)}{\eta} \tag{13}$$

$$\frac{\Delta(C_{mn})}{C_{mn}} = \frac{\Delta(LCOE)}{LCOE} + \frac{\Delta(\eta)}{\eta} \tag{14}$$

$\frac{\Delta(C_{mn})}{C_{mn}}$ and $\frac{\Delta(LCOE)}{LCOE}$ are both negative, therefore,

$$\left|\frac{\Delta(C_{mn})}{C_{mn}}\right| = \left|\frac{\Delta(LCOE)}{LCOE}\right| - \left|\frac{\Delta(\eta)}{\eta}\right| \tag{15}$$

$$\left|\frac{\Delta(C_{mn})}{C_{mn}}\right| = \left|\frac{\Delta(C_{wn})}{C_{wn}}\right| - \left|\frac{\Delta(\eta)}{\eta}\right| \text{ where } \left|\frac{\Delta(C_{wn})}{C_{wn}}\right| = \left|\frac{\Delta(LCOE)}{LCOE}\right| \tag{16}$$

This relationship (Eq. (13)) equates the fractional change in LCOE with time to the fractional change in the annualized initial system installation cost, C_{mn}, minus the fractional change in module efficiency, η, again with time. As the cumulative volume of PV modules produced and sold increases with time, this volume will eventually double multiple times; the number of doubling events is represented by N_d. For each doubling of the PV module cumulative volume produced, the module cost is reduced by 20% as shown in the 80% learning curve given in Fig. 3 [17,18]. This figure illustrates the historical economies of scale experienced in producing increasing quantities of solar electric modules, and is the basis for decreasing the module cost of manufacture used in this study.

[2] This analysis illustrates simple relationships that help visualize the dominant factors impacting LCOE in PV cell and module development. It is not intended to perform accurate and comprehensive analyses. The NREL "Solar Advisor Model" is a good tool for performing such analyses [2].

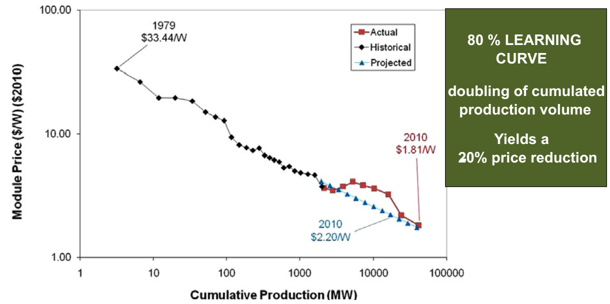

Fig. 3. PV Module experience (or learning) curve (used with permission of the EU PVSEC [8]) illustrating the economy of scale available to solar cell cost reduction.

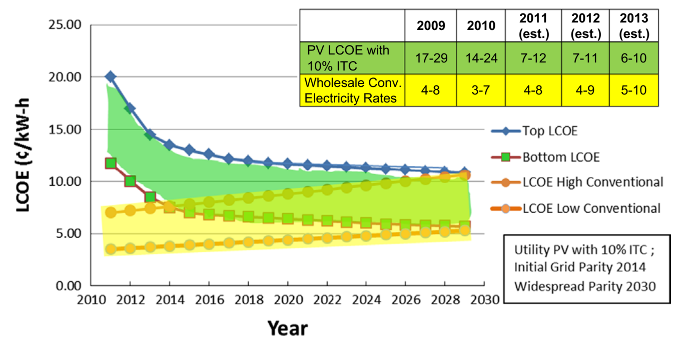

Fig. 4. U.S. Department of Energy projected PV growth and electricity cost targets. Top and bottom LCOE define the upper and lower bounds of the DOE cost targets assuming accelerated PV market growth in first 5–6 years. High and low LCOE conventional represent the bounds of cost targets for electricity produced from conventional energy sources, e.g. coal, nuclear and gas generators [9,10]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
Source: Lushetsky J. Solar technologies program, US-DOE. In: Proceedings of the 25th EU PVSEC. Valencia, Spain; September 2010 and Fthenakis V. Sustainability metrics for extending thin-film photovoltaics to terawatt levels. MRS Bulletin 2012;37(4), 425–30. (used with permission Fthenakis V., Columbia Univ.)

Consequently,

$$\left|\frac{\Delta(C_{wn})}{C_{wn}}\right| = \left|\frac{\Delta(LCOE)}{LCOE}\right| = \left|(1-0.8^{N_d})\right| \tag{17}$$

$$\left|\frac{\Delta(C_{mn})}{C_{mn}}\right| = \left|\frac{\Delta(C_{wn})}{C_{wn}}\right| - \left|\frac{\Delta(\eta)}{\eta}\right| = \left|(1-0.8^{N_d})\right| - \left|\frac{\Delta(\eta)}{\eta}\right| \tag{18}$$

$$\left|\frac{\Delta(C_m)}{C_m}\right| = \left|\frac{\Delta(C_w)}{C_w}\right| - \left|\frac{\Delta(\eta)}{\eta}\right| = \left|(1-0.8^{N_d})\right| - \left|\frac{\Delta(\eta)}{\eta}\right| \tag{19}$$

The latter expression (Eq. (19)) can be used to perform two different calculations to attain parity with the LCOE of conventional energy generation. One is related to time in years and the other is related to the sustained growth of the PV market. One can (1) choose either a fixed number of years and calculate the required PV module market growth rate or (2) choose a fixed annual growth rate of the PV market and calculate the required number of years. In both instances the PV module 80% Learning Curve (Fig. 3) is used to relate $|\Delta(C_w)/C_w|$ to N_d, thereby constraining the analysis by the learning curve, i.e., by the historical economies of scaling PV.

Fig. 4 gives a U.S. Department of Energy projection of the declining LCOE of PV compared with the LCOE of electricity produced by conventional generation [19]. The green declining curve represents the LCOE projected for PV and the slightly increasing yellow curve represents the wholesale LCOE for

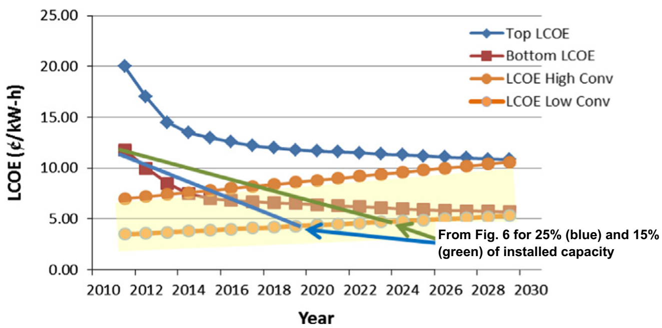

Fig. 5. Digitized approximation of the U.S. Department of Energy projected PV growth and electricity cost target given in Fig. 4. Top and bottom LCOE define the upper and lower bounds of the DOE cost targets for PV assuming accelerated PV market growth in first 5–6 years. High and low LCOE conventional represent the bounds of cost targets for electricity produced from conventional energy sources, e.g. coal, nuclear and gas generators [9]. The green and blue straight lines represent the slopes of the green and blue data plots in Fig. 6 normalized to the 2011 data point [11.5 (¢/kW-h)] for the "Bottom LCOE" curve in this figure. These straight lines, representative of constant growth rate of the PV market and normalized to the 2011 LCOE of 11.5 (¢/kW-h), predict initial parity with conventional energy sources between 2015 and 2017 and full parity between 2019 and 2024. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

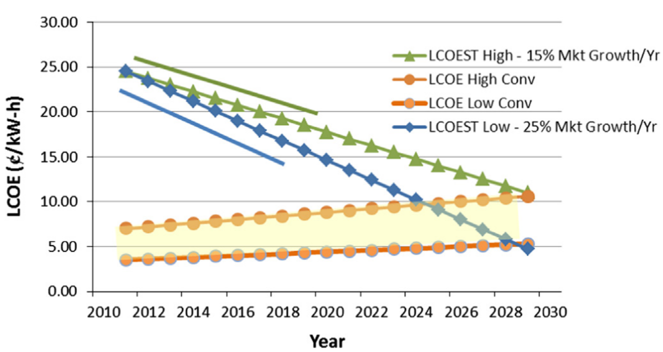

Fig. 6. Calculated projections of LCOE for two constant percent annual growth rates in the PV market. "High—15% Mkt Growth/Yr" and "Low—25% Mkt Growth/Yr" LCOE defines bounds of cost targets for PV assuming constant PV market annual growth of 15% and 25% per year for the entire 18 years.[3] These two projections start at the DOE projection of 24.5 ¢/kW-h in 2010 (Fig. 4). The high and low LCOE conventional represent the bounds of cost targets for electricity produced from conventional energy sources, e.g. coal, nuclear and as generators [9]. The green and blue solid lines represent the slopes of the green and blue data plots, for transfer to Fig. 5 above. These two scenarios (LCOEST high and LCOEST low) project PV will first reach parity with conventional sources between 2024 and 2029. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

conventional energy projected to 2030. In this instance, PV is projected to first reach parity with conventional energy in 2014 and to reach full parity by 2030. The curves given in Fig. 4 are approximated in digitized form in Fig. 5 for ease of analysis.

The steep negative slope of the DOE projection for PV LCOE in 2011 decreases as the projection approaches 2030; this is caused by an assumed large initial annual growth in the PV market in 2011 (~50%/year) decreasing to ~7% /year in 2030.[3] These assumptions for the PV annual market growth rate in 2011–2014 have a major effect on when PV begins to reach parity with conventional energy sources.[3] This is illustrated in Figs. 5 and 6.

[3] The percent growth of the PV market is defined as the percent increase in the installed PV base. Thus a growth of the PV market of 50% is equal to a 50% increase in the installed PV base.

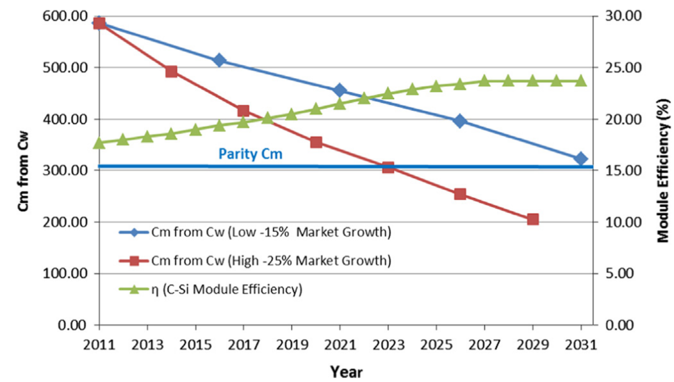

Fig. 7. Projection of C_{mn} derived from C_{mn}/η and $1/\eta$ for a market growth rate of 15%/yr (high) (blue curve) and 25%/yr (low) (red curve) and projected efficiency increase for c-Si modules. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As shown above, the Levelized Cost of Energy, LCOE, is linearly dependent on the annualized initial cost of installation, C_{mn}, and inversely on the PV module efficiency, η, in Eq. (6).

Given two assumptions, the question now becomes: what value of $\Delta(C_m)/C_m$ is required to obtain the fractional change in LCOE needed to achieve first parity for both scenarios discussed above. The two assumptions are: (1) A fixed value of $\Delta(LCOE)/LCOE$ specified by the DOE projection for LCOE in 2011 (24.5 ¢/kW-h in 2011) given in Fig. 6 over the time required to first achieve parity; and (2) A fixed value of $\Delta(\eta)/\eta$ for a c-Si PV module, achieved over the same time. For the linear projections given in Fig. 6 (based upon DOE data given in Fig. 5), $\Delta(LCOE)/LCOE$ is -59% and $\Delta(\eta)/\eta$ is $+25\%$. The fractional reduction in the initial installed cost of a PV system, $\Delta(C_m)/C_m$, is -34%. This illustrates the point that for PV systems to become cost-competitive with conventional large scale utility generation systems, reduction of the initial installed cost of the PV system and increased module efficiency are both required. The results of this analysis are given in Fig. 7. They illustrate reduction of the initial installed cost in time for two market growth rates of 25% and 15% per year and for the Si PV module development profile shown. In this example, reduction of the annual PV market growth rate from 25% to 15% extends the point in which first parity is achieved by 9 years.

5. Discussion

How does this relate to a PV technology roadmap and to the PV research community? First, the data for C_m and η, given in Fig. 7 for the two scenarios discussed above, define technology requirements paths for C_m and η needed to realize a cost-competitive PV system in 4–6 years for an initial LCOE of 11.8 ¢/kW-h and 11–20 years for an initial LCOE of 24.5 ¢/kW-h. The projected increase of 25% in the efficiency of mono-crystalline silicon solar cells and the related increase in module efficiency are the maximum increases projected over the time horizon of this analysis.

Does a Moore's Law-like relationship exist for photovoltaics? Our answer is yes—as shown above, a reduction of the LCOE of 59% for PV systems over an 11-year period requires a reduction in the installed system cost of 34% combined with an increase in cell and module efficiency of 25% for a constant 25% per annum growth of the PV market over the 11-year period. To first order, this "Law" can be re-stated approximately as a 50% reduction in LCOE can be achieved by a 30% reduction in the initial installed cost of the system combined with a 20% increase of c-Si solar module manufacturable efficiency over a time period less than 10 years given an annual growth of the PV market of 25%.

However, there is a very important difference between Moore's Law for microelectronics and a similar relationship for PVs. Over a period of 40 years, Moore's Law defined transistor size and density scaling over eight orders of magnitude from a few tens of transistors per cm^2 to a few billions of transistors per cm^2. Conversely, the available range for reducing LCOE by increasing the efficiency of solar cells is quite restricted. For example, for mono-crystalline-Si cells the available range of fractional percent increase in cell efficiency is from 20% to 25% or possibly a bit higher [20,21]. For thin-film cells the range may be a bit broader from 15% up to 28% [22,23]. Reduction to practice of new ideas for photovoltaic energy conversion may increase this maximum up to 70–80% a factor of 4 × above the current manufacturable efficiency of ~20% for c-Si cells [24]. This constraint in the available range for increasing cell efficiency, therefore, places the major burden of obtaining larger decreases of LCOE upon achieving larger fractional decreases in the installed system cost.

In addition, comparison of data given in Figs. 4–6 delineating the DOE projection for the LCOE employing accelerated market growth (Fig. 4—green curves and Fig. 5—blue and red data) with those reported in this paper for constant market growth (Fig. 6—green and blue data points), illustrates that stimulating market expansion within the next few years could enable economies of scale (i.e. the Learning Curve) to accelerate lowering of the cost of PV energy to reach parity with conventional utility generated energy within the near future. In this example, illustrated in Fig. 5, the nonlinear DOE projection for LCOE (red data points) indicates PV begins to reach parity with conventional energy in 2014. Projecting the year of first parity for a market annual growth rate of 25% applied to the bottom linear curve for LCOE (solid blue straight line) beginning at the lower 2011 cost of PV energy of 11.8 ¢/kW-h is 2016 and for a market annual growth rate of 15% (solid green straight line) is 2018.

To reach first parity, the initial installed cost of PV systems needs to be reduced by 50% from approximately \$600/m^2 to \$300/m^2 with an increase in c-Si module efficiency to 24% AM1.5. Example trajectories for C_m (initial system cost) again for market growth rate of 25%/Yr (red curve) and 15%/Yr (blue curve) are given in Fig. 7. Also, given in Fig. 7, is a challenging projected profile of module efficiency (green curve), η increasing from 20% to 24%, assumed in deriving the trajectory for C_m. These profiles for C_m and η form a basis required to drive a technology roadmap for lowering the installed cost and for increasing the module efficiency necessary to reach first parity for two rates of market growth, 25% and 15%. The completed roadmap for mono-crystalline silicon module efficiency would consist of specifying the solar cell and module structures and solar cell material and device parameters consistent with the cost objectives to advance the module in time along the assumed trajectory.

This simple analysis illustrates possible roles for both industry efforts to lower the installation costs and for university research to discover new paths for higher efficiency PV cells. It can also be used to provide a simple methodology for developing technology defining scenarios for any particular PV technology targeting a particular date for achieving parity in Levelized Cost of Energy with conventional utility power. In addition, the impact of financial incentives on the market growth rate can be estimated.

Appendix

Revised method proposed for calculating LCOE of photovoltaic systems

The Levelized Cost of Energy is defined as "that cost, if assigned to every unit of energy produced or saved by the system over the analysis period, will equal the total life cycle cost when discounted back to the base year." The total life cycle cost (TLCC) is defined as the total cost of a system incurred through ownership of that system over the system's life span or the period of interest to the owner [25,26]. Calculation of TLCC includes all costs (capital investment, operating and maintenance, financing, taxes, residual value, etc.) incurred over the life of the system and discounted back to the first year using a present value calculation. [25]

The LCOE for energy systems is typically calculated using the formula [25]

$$LCOE = (Total\ cost\ of\ the\ PV\ system\ over\ its\ life) / (Total\ Electrical\ Energy\ produced\ by\ the\ system)$$

$$LCOE = \frac{Ct}{Wte} = \frac{\sum_{n=1}^{n+N}[(C_{mn}/(1+D)^n) + ((C_{mn} \times I \times N)/(1+D)^n) + (C_{omn}/(1+D)^n) + (C_{inv}/(1+D)^n)]}{\sum_{n=1}^{n+N} Q_n (1-i)^n/(1+D)^n} \tag{A1}$$

This approach is based upon an exhaustive and comprehensive analysis of the cost of energy published in 1995 [25]. In this analysis, both the total cost of the system, represented by Ct, and the total quantity of energy produced by the system over its lifetime, represented by Wte, are discounted back to the first year on an annual basis by the discount rate, D. This means that both the numerator and the denominator of Eq. (A1) are discounted by D. Discounting a variable, such as cost, Ct, which has a time value, is quite appropriate. However, discounting a parameter, such as the average annual solar energy insolation, $Wten$, that is time invariant over the life of the system, is not appropriate. This is shown below.

The analysis in [25] expresses the total life cycle cost, TLCC, of a system as

$$TLCC = \sum_{n=1}^{n=N} \frac{Q_n \times LCOE}{(1+D)^n} \tag{A2}$$

or

$$LCOE = TLCC / \left\{ \sum_{n=1}^{n=N} [Q_n/(1+D)^n] \right\} \tag{A3}$$

The numerator of Eq. (A2), $Q_n \times LCOE$, is the levelized or discounted cost of energy produced in the nth year. This quantity is then discounted a second time by application of $(1+D)$ to $Q_n \times LCOE$. To justify application of the discount factor $(1+D)$ to the (time invariant) quantity, Q_n, the authors [25] state in a footnote: "Even though it may appear in this formula (Eq. (A3)) that quantities are being discounted, this is actually a direct result of the algebra carried through from the previous formula (Eq. (A2)) in which revenues were discounted".

In our view, Eq. (A2) discounts a quantity, $LCOE$, which, by definition, is discounted already. Also, since Q_n is the annual solar insolation averaged over several years, it is a time invariant quantity not subject to being discounted. Therefore, the quantity $Q_n \times LCOE$ should not be discounted.

One approach to examining this question is to use the definition of TLCC stated in [25] as their Eq. (4)–(2) (page 43)

$$TLCC = \sum_{n=1}^{n=N} \frac{C_n}{(1+D)^n} \tag{A4}$$

where C_n is the total cost expended in the nth period.

Eq. (A2) can be re-written as

$$\sum_{n=1}^{n=N} \frac{Q_n \times LCOE}{(1+D)^n} = \sum_{n=1}^{n=N} \frac{C_n}{(1+D)^n} \tag{A5}$$

Eq. (A5) can be expanded in its terms related to each of the N years

$$\frac{Q_1 \times LCOE}{(1+D)^1}+\frac{Q_2 \times LCOE}{(1+D)^2}+\ldots+\frac{Q_n \times LCOE}{(1+D)^n} = \frac{C_1}{(1+D)^1}+\frac{C_2}{(1+D)^2}+\ldots+\frac{C_n}{(1+D)^n}. \tag{A6}$$

Terms of Eq. (A6) related to a given year can be equated. So for the nth year ($n \le N$) this equality is

$$\frac{Q_n \times LCOE}{(1+D)^n}=\frac{C_n}{(1+D)^n} \tag{A7}$$

This gives

$$LCOE=\frac{C_n}{Q_n} \tag{A8}$$

This yields a result for LCOE that does not discount the annual cost, Cn. This contradicts the definition of *LCOE*, and invalidates the original formulation for *LCOE* given in Eq. (A2).

A different approach which obtains the same result begins with Eq. (A5), and the observation stated above that the annual operation and management cost, C_{omn}, and the annual depreciation cost, C_{inv}, of the new inverter installed in the mth year are directly proportional to the annual depreciation cost of the initial installation, C_{mn}. The constant of proportionality for C_{omn} is typically $P_{om}=0.0012$ [14] and for C_{inv} is $P_{inv}=0.0763$ [15,16]. Also, as defined above, C_{mn} is assumed to be a constant equal to C_m/N. These are key approximations in that they reduce the relationship for LCOE to a simple linear equation, as shown in Eqs. (5)–(7) above and are reproduced in Eqs. (A9)–(A11) below.

$$LCOE=\frac{Ct}{Wte} = \frac{\sum_{n=1}^{n=N}[(1/(1+D)^n)+((I \times N)/(1+D)^n)+(P_{om}/(1+D)^n)+(P_{inv}/(1+D)^n)]}{5.38 \times 365 \times \sum_{n=1}^{n=N}(1-i)^n} \times \left(\frac{C_{mn}}{C_f \times \eta_c}\right) \tag{A9}$$

$$LCOE=Constant_m \times \left(\frac{C_{mn}}{C_f \times \eta_c}\right), \tag{A10}$$

where

$$Constant_m=\frac{\sum_{n=1}^{n=N}[(1/(1+D)^n)+((I \times N)/(1+D)^n)+(P_{om}/(1+D)^n)+(P_{inv}/(1+D)^n)]}{5.38 \times 365 \times \sum_{n=1}^{n=N}(1-i)^n} \tag{A11}$$

Given, that in Eq. (A5): $C_1 \sim C_2 \sim C_3 \sim \ldots \sim C_n \sim \ldots \sim C_N$ and $Q_1=Q_2=Q_3=\ldots=Q_n=\ldots=Q_N$

Eq. (A5) can be written as

$$Q_n \times LCOE \times \sum_{n=1}^{n=N}\frac{1}{(1+D)^n}=C_n \times \sum_{n=1}^{n=N}\frac{1}{(1+D)^n} \tag{A12}$$

which yields for LCOE

$$LCOE=\frac{C_N}{Q_n} \tag{A13}$$

Once again, this shows that in the formulation of Eq. (A2), LCOE does not discount the annual cost, C_n, which contradicts the definition of *LCOE* and invalidates the original formulation for *LCOE* given in Eq. (A2).

A more satisfactory formulation for LCOE is

$$TLCC=\sum_{n=1}^{n=N}Q_n \times LCOE \tag{A14}$$

Solving for LCOE

$$LCOE=\left(TLCC/\sum_{n=1}^{n=N}Q_n\right) \tag{A15}$$

$$LCOE=\sum_{n=1}^{n=N}\frac{C_n}{(1+D)^n}/\sum_{n=1}^{n=N}Q_n \tag{A16}$$

This yields a result in Eq. (A16) that is consistent with the definition of LCOE which requires discounting the time-dependent costs incurred in the nth year back to the first year, but does not require discounting the constant amount of annual solar insolation incident on a PV system over its lifetime.

Based on this analysis, we propose the expression for LCOE given in Eq. (A16) is the preferred formula.

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